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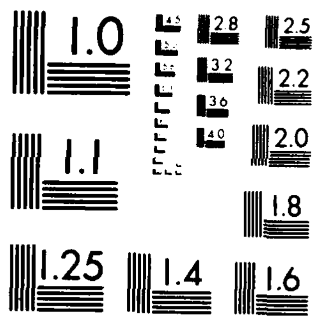

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EFFECT OF TRANSFORMED BETA MORPHOLOGY AND OTHER STRUCTURAL FEATURES ON MECHANICAL PROPERTIES IN Ti-6Al-4V

by

Cao Chunxiao, Wang Jinyou and Shen Quiqin

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Effect of Transformed Beta Morphology and Other Structural Features on Mechanical Properties in Ti-6A1-4V

Cao Chunxiao, Wang Jinyou and Shen Quiqin

Abstract

A study of the relations between the alloy structure of Ti-6Al-4V and its characteristics shows that its tensile ductility, fatigue strength (high cycle and low cycle fatigue), fracture toughness, creep resistance, and other characteristics are not only determined by whether it is an acicular structure or an equiaxed structure, but also depend on the primary alpha percentage, the original beta grain size, the transformed beta morphology, and other conditions. Among these conditions, the transformed β structure morphology is especially an important factor. With respect to one property, the acicular structure is superior to the equiaxed structure under one condition. However, under another condition, the former may be close to or poorer than the latter. Therefore, it is impractical to compare these two types of structures in general. A comparison of the overall characteristics shows that, among all the structures mentioned in this paper, the basketweave structure is the optimum and the aligned structure is the worst.

Due to the importance of the microscope structure in the quality control of titanium alloy products, various countries have already conducted a great deal of studies on the relations between the microscopic structures of titanium alloys and their mechanical characteristics. Many beneficial results have been obtained. However, up to the present moment, there still are some problems in the production and application of titanium alloys which must be resolved urgently. Due to the fact that some of the experiments carried out in and out of the country seemed to be mutually contradictory, therefore, many differences emerged from the technical and quality control microscopic structure points of view. For example, with regard to the

problem of whether the fatique characteristic of one of the two major types of structures of the acicular α structure and the equiaxed α structure is better or worse than the other, some differences exist academically over a long period of time.[1-7] The purpose of this work was to explore the internal correlation which actually exists in the middle of the confusing surface phenomena.

Materials and Methods

The composition of the Ti-6Al-4V alloy used in this study is listed in Table 1.

Al	V	Fe	C	Si	O_2	N_2	H_2	Ti
6.39	4.13	0.07	0.03	0.04	0.10	0.023	0.006	余量 1.

Table 1. The Chemical Composition of the Ti-6Al-4V Alloy (weight %) 1. balance

The same type of furnace was used to prepare rod materials (ϕ 20～28mm) of various transformed β structures, initial α contents, and effective β grain sizes by using different heat treatments and hot rolling techniques. After the rod materials were annealed (800°C, 1 hour, air cooling), their microscopic structures and mechanical characteristics were compared.

The various characteristics data reported represented the mean values obtained by using 3～5 samples.

Results and Discussion /2

Some typical micro-structures are shown in Figure 1 (see the attached graph). The variation of the transformed β structure state (in the equiaxed α structure A→ B→ C, in the aligned

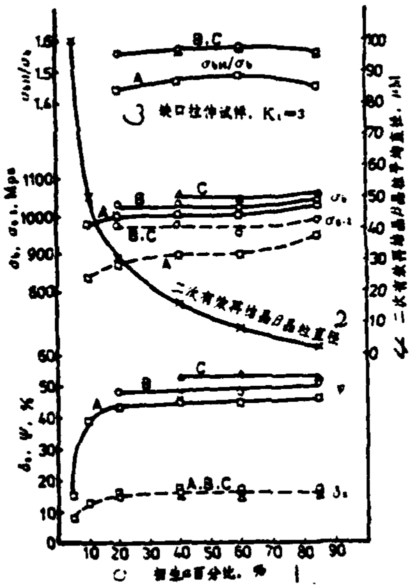

Figure 2. The effect of various structural properties in the equiaxedly structured Ti-6Al-4V alloy on its tensile characteristic. A, B, and C are different transformed β structure states.

1. primary α percentage
2. β grain diameter in the effective recrystallization for the second time
3. notched tensile specimen
4. average diameter of the effectively recrystallized β grain.

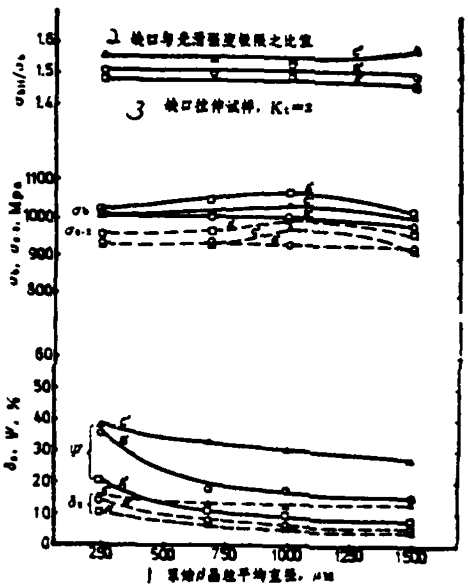

Figure 3. The effect of the various structural characteristics in the acicularly structured Ti-6Al-4V alloy on its tensile properties. A', B', and C' are different transformed β structural states.

1. average diameter of the primary β grain, μm
2. ratio of the notched and smooth strength limits
3. notched tensile specimen $K_t = 3$.

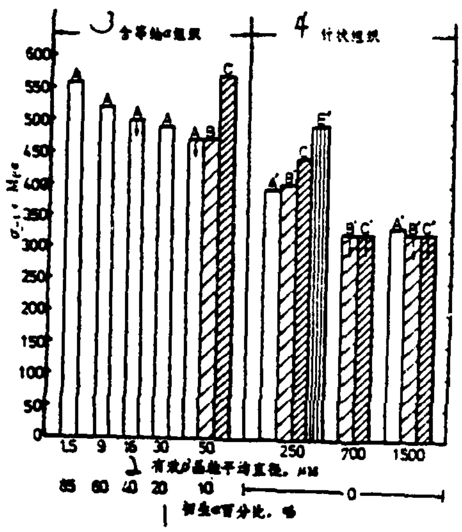

Figure 4. The effect of various structural characteristics on the high cycle fatigue strength (10^7 cycles) of the Ti-6Al-4V alloy. R = -1. A - C and A' - E' are different transformed β structural states.

1. primary α percentage, %
2. average effective diameter of β grains, μM
3. equiaxed α structure
4. acicular structure

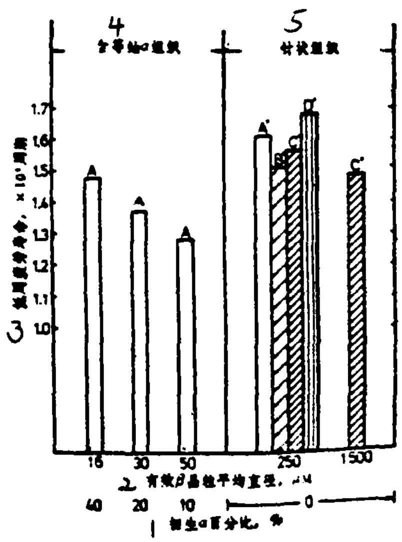

Figure 5. The effect of various structural characteristics on the low cycle fatigue lifetime of the Ti-6Al-4V alloy. $R = 0.1$, $\sigma_{max} = 600MPa$, $K_t = 2.4$, $f = 0.2Hz$. A and A' - D' are different transformed β structural states.

1. primary α percentage
2. average effective β grain diameter, μm
3. low frequency lifetime, x 10^4 cycles,
4. with equiaxed structure,
5. acicular structure.

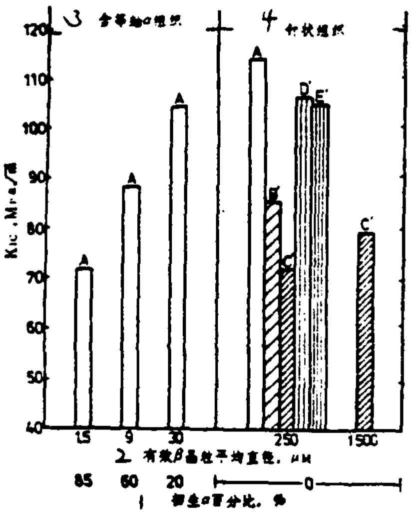

Figure 6. The effect of various structural characteristics on the fracture toughness of the Ti-6Al-4V alloy. A and A' - E' are different transformed β structural states. /3

1. primary α percentage, %
2. average effective β grain diameter, μM,
3. with equiaxed α structure,
4. acicular structure

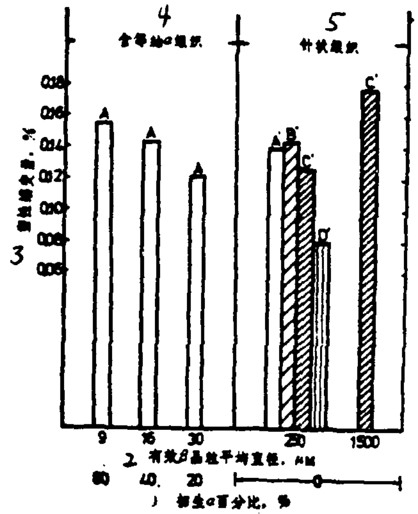

Figure 7. The effect of various structural characteristics on the plastic creep variation of the Ti-6Al-4V alloy. 400°C/295MPa/100hrs. A and A' - D' are different transformed β structural states.

1. primary α percentage, %
2. average effective β grain diameter, μm
3. plastic creep variation %
4. with equiaxed α structure
5. acicular structure

structure where α is the primary one $A' \to B' \to C'$, and in the basket woven structure $D' \to E'$) indicates that the α flatness, the continuity of β, and the completeness of the α grain boundary are gradually decreased. The comparison of the D' and E' states further shows that the latter contains individual original β grains which are formed by even more and finer grains whose directions are close to the α structure than the former.

With regard to the acicular structure, "the effective grain "means" the prior β grain." For a structure containing an equiaxed α structure, it means the "effectively recrystallized β grain" surrounding the prior α.

The test results of various mechanical properties correlated to the micro-structural characteristics are shown in Figures 2~7.

The Equiaxed α Structure

With regard to an equiaxed structure, people usually place their emphasis on the effect of the primary α content. It is usually done in the quality control of the production of titanium alloys.[6.8.9]

For example, the metallographic standard of the Low & Low Company in England specified that the primary α content should not be lower than 30%[11]. However, the state of the transformed β structure in the equiaxed α structure is usually neglected. This study happened to prove that the transformed β structural state has an important effect with some regularity on the properties of an equiaxed α structure. For example, one can find out from Figure 2 that as long as the equiaxed primary α content is the same (no matter what the content is), the room temperature tensile strength, fracture surface contraction ratio, and notch sensitivity coefficient (the ratio of the strength limits with and without the notch) of an equiaxed α structure always increase as the transformed β structural state changes from A to B to C. Such a phenomenon can be explained by using the following viewpoint: the flatness of the acicular α structure and the decrease of β continuity cause the growth of the cavity and the difficulty in coupling. This leads to the greater deformation and higher plasticity prior to fracture. Consequently,

it also favors the continuous adjustment of stress and strain in the area neighboring the notch. Figure 4 shows that when the transformed β structural states are all A, the lowest high cycle fatigue strength is shown in a structure containing 10% primary α structure among all the equiaxed α structures. However, when the transformed β structure is changed to C, although the primary α content remains to be 10%, its high cycle fatigue strength is already higher than those of the equiaxed α structures whose /4
transformed β structural states are A (including the equiaxed structures with high primary α contents). From this one can see that the transformed β structural state has an even more important effect as compared to the primary α content. This is to say that although increasing equiaxed primary α content (the corresponding refining of the effective β grain) favors the dislocation activities and the dispersion of the strain on the slipping band which increases the resistance against the formation of nuclei of a fatigue crack, yet the high degree of twist of the acicular α structure in the transformed β structure, the shattering and breaking of the preserved β structure, and sphere formation have an even more favorable effect in this regard.

Based on the above description, if the difference in the transformed β structural state is neglected, a confusing phenomenon may be created in the relations between the primary α content and the mechanical properties. The wrong conclusions may even be obtained. On the other hand, if the transformed β structural states are distinguished and the relations between the primary α content and the mechanical properties are studied under the same transformed β structural state, then the following trends as shown in Figures 2, 4-7 can be obtained: with increasing primary α content (the effective β grain size decreasing correspondingly), the ambient temperature tensile strength, the tensile plasticity, the high cycle fatigue strength, and the low cycle fatigue strength gradually increase. The fracture toughness and the creep resistance gradually decrease. The notch sensitivity coefficient basically remains unchanged.

The Acicular α Structure

Although there have been many foreign and domestic publications on the studies of the acicular α structure, yet not too many tests were carried out in all aspects using the same type of furnace. Even fewer papers exist to systematically compare the various application characteristics of the aligned α and the basket α structures. Usually, the emphasis of the study is placed on the fatigue characteristics such as the "induction effect." Furthermore, it has already been proven that under certain conditions the aligned α structure exhibits an apparent "induction effect." Hence the low cycle fatigue lifetime was seriously shortened.[9,10,12] This experimental work shows that the weakness of the aligned α structure is not limited to this one feature. It is frequently inferior to the basket woven structure in terms of creep resistance, fracture toughness, high cycle fatigue strengths and low cycle fatigue lifetime without induction to one extent or another. It is believed that the high and low cycle fatigue characteristics of the aligned α structure are poorer than those of the basket α structure primarily because of the latter. A relatively longer skidding line does not favor the dislocation activity. The strain accumulated on the skidding line is more difficult to disperse. Therefore, it is easier to create a fatigue cracking nucleus. Increasing dimension of the α structure slice also accelerates the propagating rate of the crack. This is due to the decrease in the slowing down effect when the crack propagates to the grain boundary of the α structure.[13-15]

In an aligned α structure, when the prior β grain diameter is 0.25mm, as the state changes from A'→B'→C', the ambient temperature tensile plasticity, notch sensitivity coefficient, and high cycle fatigue strength gradually increase. The fracture toughness gradually decreases. The remaining properties do not vary according to any apparent pattern. When the transformed β structural states are the same, the ambient temperature plasticity and the high cycle fatigue strength decrease with increasing size of the prior β grain. When the prior β grain is excessively thick, although the tensile plasticity can be improved by using

methods such as the shattered α grain boundary, the distorted acicular structure, and the fractured and preserved β structure (i.e., to change state A' to B' or C'), yet it cannot be used to raise the fatigue strength. The high cycle fatigue strength of states B' and C' is still remain at a very low level (see Figure 4). Possibly due to the difference in the experimental conditions, the test result obtained by Lucas showed that the effect of the prior β grain on its fatigue characteristics is not as significant as the one obtained in this work.[7]

Comparison of the Two Major Structural Types

This experiment shows that, in the comparison to the acicular α structure and the equiaxed α structure, all the mechanical properties described in this paper do not unconditionally favor one or the other. That means the properties (including fatigue characteristics) of the two major structures can mutually be transformed under a given set of conditions. These conditions include the transformed β structural state, the primary α content, the effective β grain size and other structural characteristics. If these specific conditions are ignored in the comparison of these two major structures, it is not surprising that various conclusions and assumptions are obtained.

One can also see from the comparison of the two major structures that under most conditions the high frequency fatigue strength of the acicular structure is lower than that of the equiaxed α structure. On the other hand, the low frequency fatigue lifetime of an acicular structure is higher than that of an equiaxed α structure. This phenomenon can be explained by the following viewpoint: with regard to high frequnecy fatigue, the inception stage of the fatigue crack occupies most of the fatigue lifetime.[16,17] The high frequency fatigue strength is primarily determined by the resistance of nucleus formation for fatigue cracking corresponding to various microstructures. The increase in the equiaxed α content, however, favors the improvement of the nucleus formation resistance. Nevertheless, the low frequency fatigue is tested under a high stress.

The effect of the crack propagating stage becomes more important. /5
This favors the acicular α structure which has a zigzag crack. Propagation rate cancels or even exceeds the disadvantage of a low cracking nucleus formation resistance.

Conclusions

1. In an equiaxed α structure in the Ti-6Al-4V alloy, the transformed β structural state often has an even greater effect than that of the equiaxed primary α content. The proper method of obtaining the transformed β structures with an acicular α twisted structure, an intermittent β structure, and a shattered α grain boundary (if it exists), is an effective way to increase the ambient temperature tensile strength, tensile plasticity, notch sensitivity coefficient, and high cycle fatigue strength of an equiaxed α structure.

2. When the transformed β structural state is the same, with increasing equiaxed primary α content (correspondingly with decreasing effective β grain size), the ambient temperature tensile strength, the tensile plasticity, the high frequency fatigue strength, and the low frequency fatigue lifetime of an equiaxed α structure gradually increase. The fracture toughness and the creep resistance gradually decrease. The notch sensitivity coefficient basically remains unchanged.

3. In the acicular α structure, the creep resistance, the high cycle fatigue strength, the low cycle fatigue strength, and the fracture toughness of an aligned α structure are usually lower than those in a basket α structure. In an aligned α structure, the decrease in the completeness of the α grain boundary, the flatness of the α acicular structure, and the continuity of the preserved β structure would favor the improvement of the ambient temperature tensile plasticity, the notch sensitivity coefficient, and the high frequency fatigue strength. However, the fracture toughness is decreased. The prior β grain is thickened. It lowers the ambient temperature tensile plasticity and fatigue characteristics.

4. To generally compare the mechanical properties of the two major metallographic structures, the acicular α structure and the equiaxed α structure, is not practical. With regard to a certain property (such as the fatigue characteristic), the acicular α structure is superior to an equiaxed α structure under one set of conditions. Under another set of conditions, the former may be close to or poorer than the latter.

5. The comprehensive comparison of the mechanical properties shows that, among all the structures described in this paper, the basket structure is situated in the most favorable position. The aligned structure (especially the one with a thick prior β grain) is located in the most disadvantageous position.

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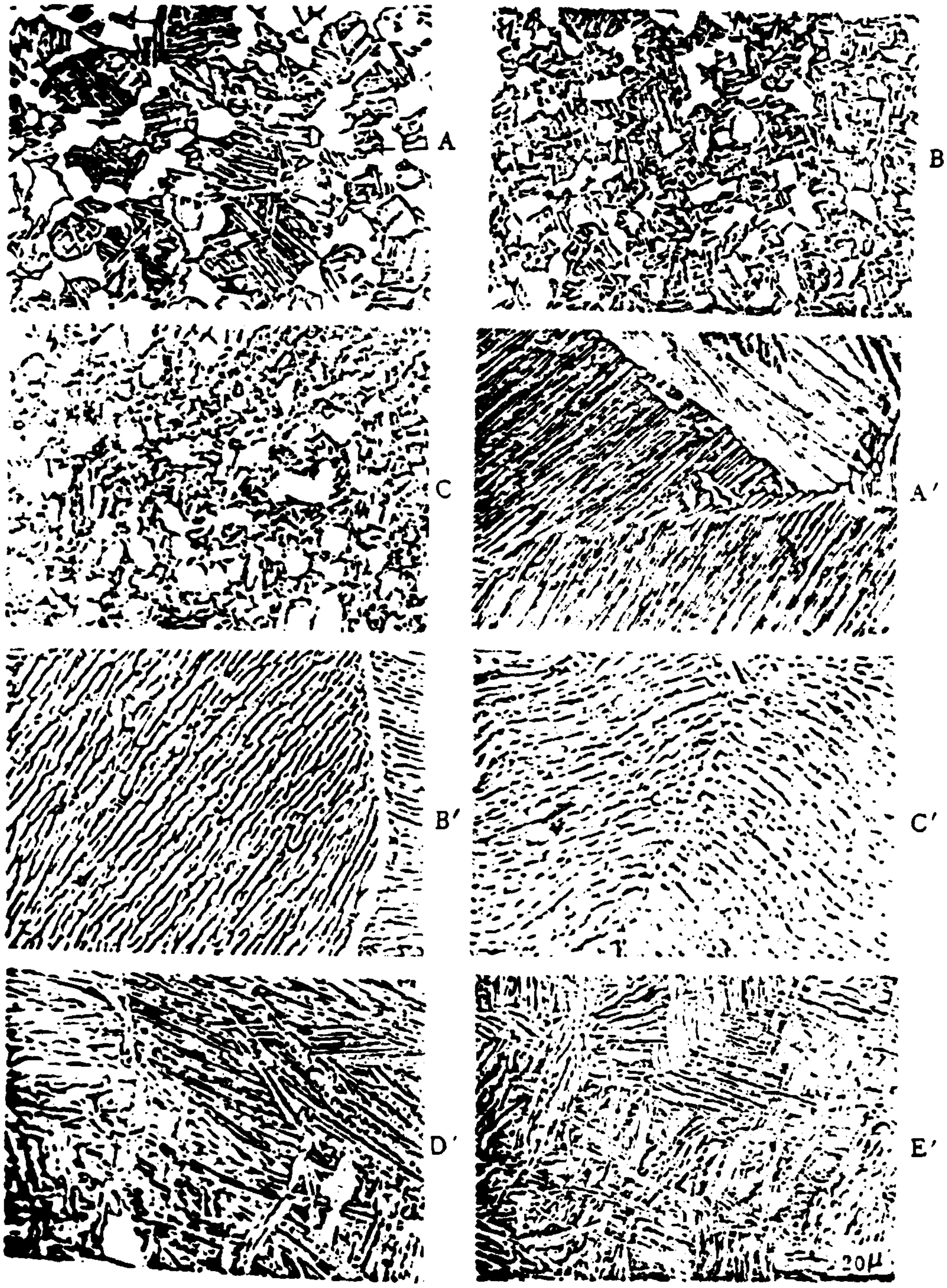

Figure 1. The Various Transformed β Structural States of the Ti-6Al-4V alloy (A-C in the equiaxed α structure and the A'-E' in the acicular structure) x 500 /6